PROJECT ID: eems041

# Hardware-Focused Connected and Automated Vehicle (CAV) Research: Experimental Results and Benefit Analysis

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Center for Transportation Research, Argonne National Laboratory

DOE Annual Merit Review
June 20th, 2018

# OVERVIEW

## Timeline

*Revised focus on EEMS for FY18*

- Project start date: 10/2017
- Project end date: 9/2018
- Percent complete: ~75%

## Highlighted Barriers

- Difficulty in sourcing accurate and traceable real-world data
- Rapid evolution of CAV technologies
- Constant advances in technology drive unexpected consequences for CAVs

## Budget

- FY17 Funds - $2,000k
  *Previous focus on vehicle technology evaluation*
- **FY18 Funds – $1,000k**
  100% DOE Funds

## Partners

- Argonne and DOE Vehicle Modeling & Controls PIs
- DOE-SMART consortium researchers
- Illinois Institute of Technology
- HPC-Big Data researchers

# RELEVANCE - Fundamental Disruption is Occurring in Transportation

## DOE Energy Efficient Mobility System (EEMS) Strategic Goals

**STRATEGIC GOAL #1**
Develop new tools, techniques, & core capabilities to understand & identify the most important levers to improve the energy productivity of future integrated mobility systems.

**STRATEGIC GOAL #2**
Identify & support early stage R&D to develop innovative technologies that enable energy efficient future mobility systems.

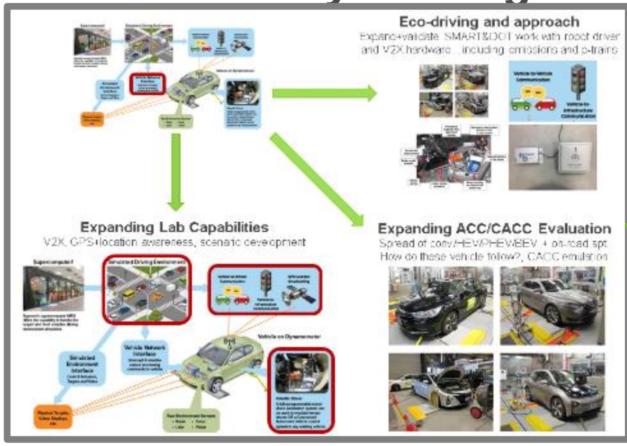
**STRATEGIC GOAL #3**
Share research insights, and coordinate and collaborate with stakeholders to support energy efficient local and regional transportation systems.

## Supporting DOE's research within the expanded context of vehicle connectivity and automation

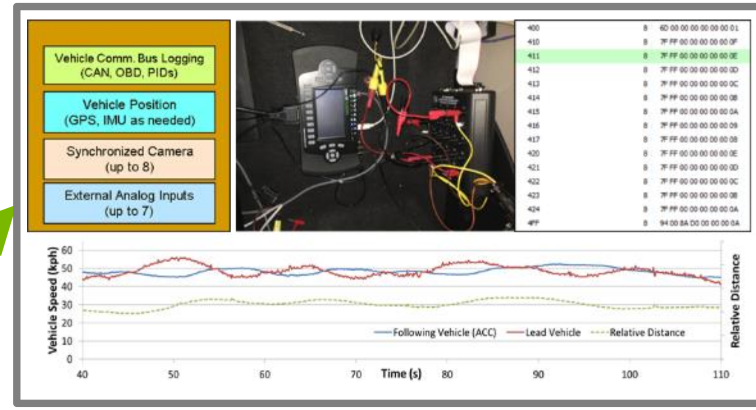
- Building upon existing experimental expertise & best-practices
- Providing tractable and robust laboratory data (when applicable)
- Overlaying state-of-the-art vehicle technologies in a CAV context
- Expanding what is possible within an experimental context

# APPROACH – FOUR OVERLAPPING RESEARCH THRUSTS

## Laboratory Testing

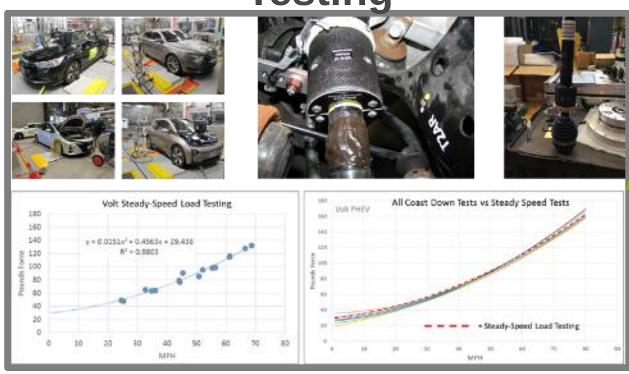



## Collect Realistic, On-road Behavior

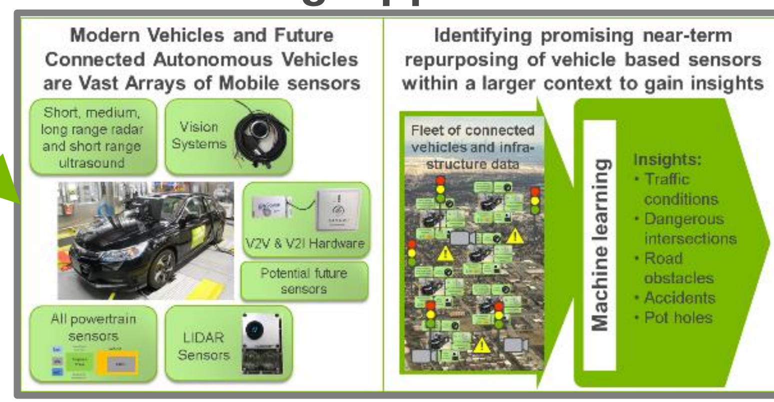



**Hardware Focused Research**

## Targeted On-Road & Track Testing




## CAVs Enabled Awareness and Sensing Opportunities



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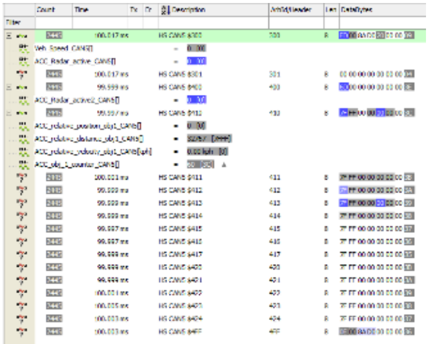
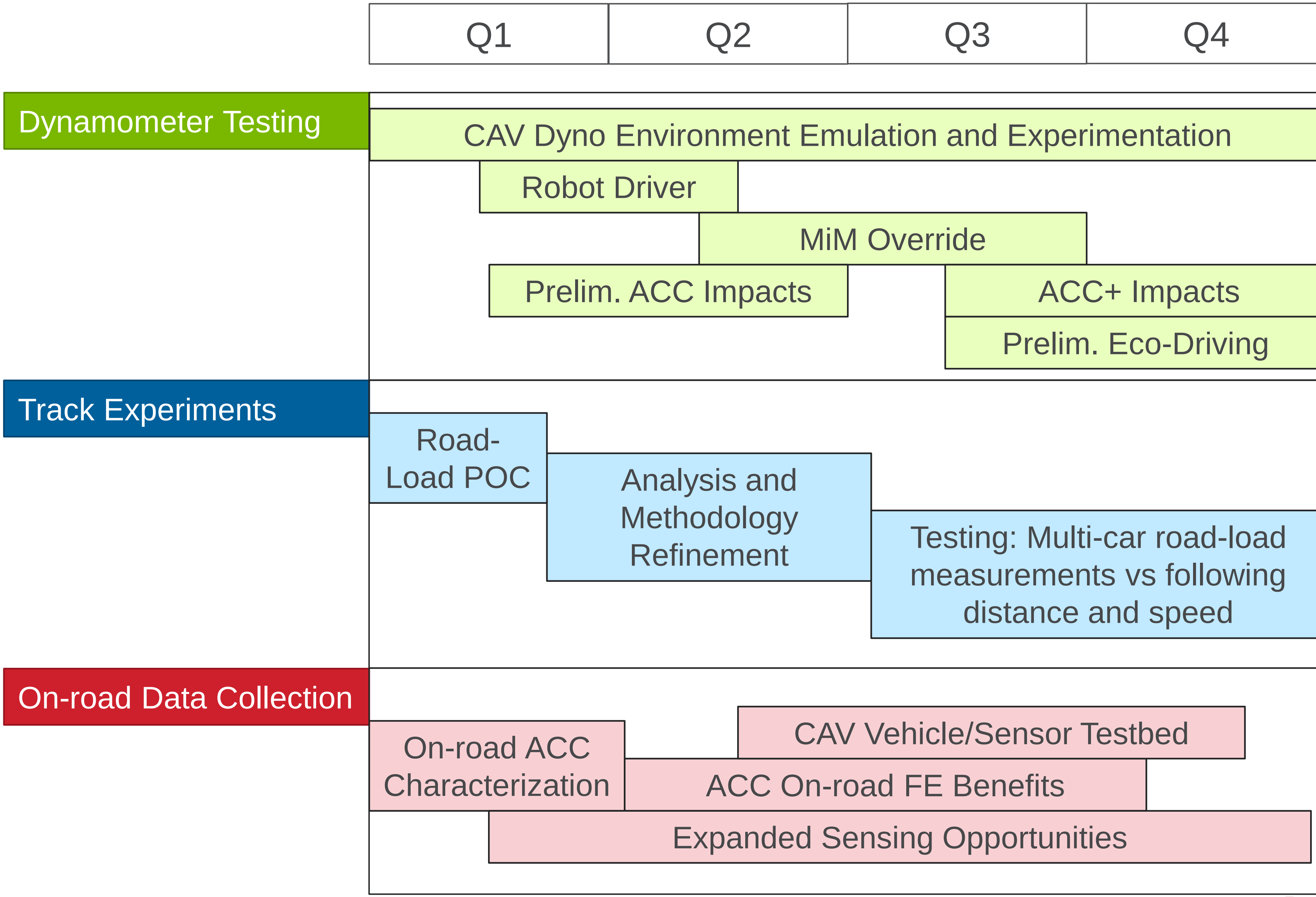
# APPROACH

**High-fidelity data regardless of environment:**

- Vehicle-based messages from CAN/diagnostics
- Decoded messages for ACC/related systems
- Cameras (up to 8 time sync'd)
- Direct axle torque measurement
- GPS data @ 5Hz (std.) to 20Hz (supplemental hardware)
- Direct in-line fuel measurement
- Man-in-the-middle capability for further experimentation



# FY18 MILESTONES AND PROJECT OVERVIEW



# Accomplishments: Energy-Centric CAV Laboratory

## Three broad categories of “energy-intelligent” behaviors

1) Location Awareness 2) V2X Communication and coordination 3) In-vehicle technologies

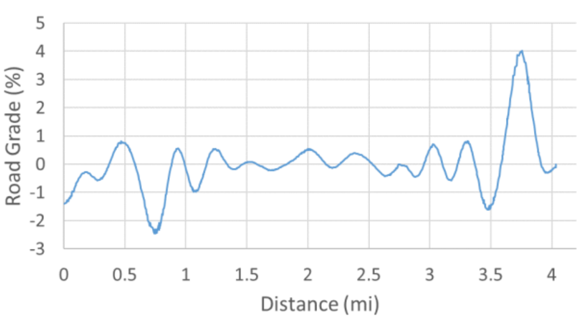
Free-running Baseline Road-load Simulation

### Emulated “Driver” and Controls

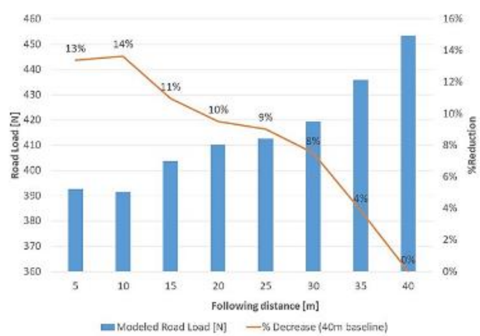
1) **Processed Cycles – human driver**
   - \+ Fast, historical crossover
   - \- Trace following versus “driving”
2) **Robot driver adapted for CAVs**
   - \+ Adaptable to non-CAVs vehicles
   - \+ Very repeatable control inputs
   - ? Subject to vehicle pedal mapping/dynamics
3) **Generalized Man-in-the-Middle**
   - \+ Override traction controls directly
   - \+ Override other controls (when possible)
   - \+ Intercept and modify specific signals (lead car)

### Emulated “Tractive” Environment

Distance-based Road Profiles



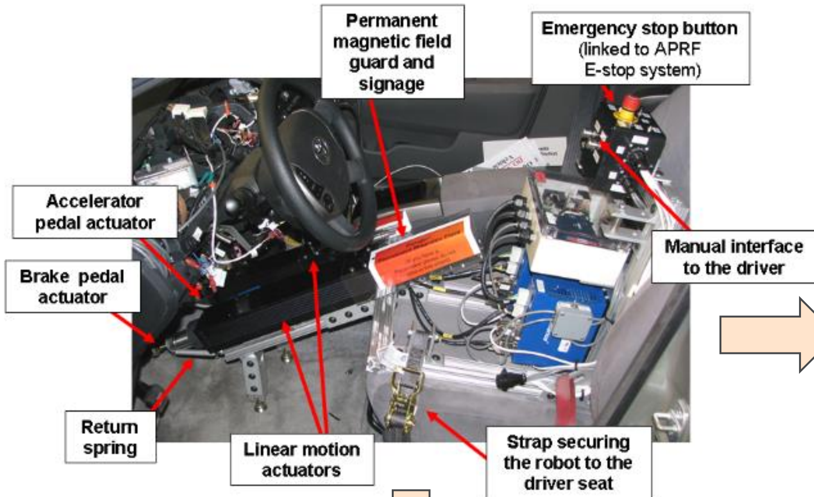

Dynamic Road Load (i.e. aero from platooning)



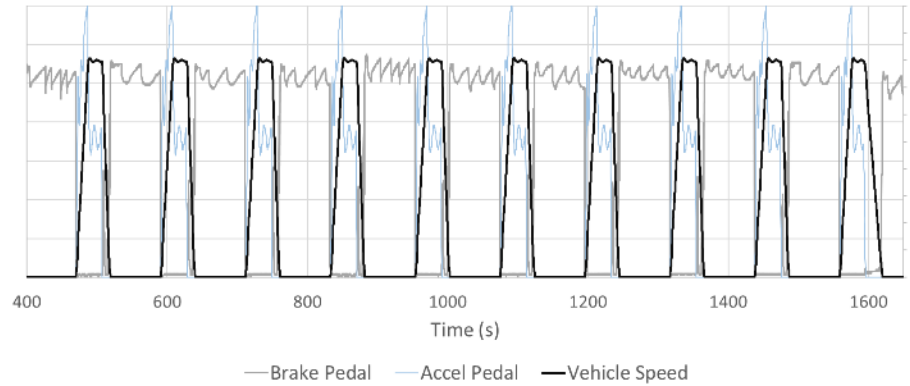

Flexible “Perception” Layer

“Environmental” Emulation

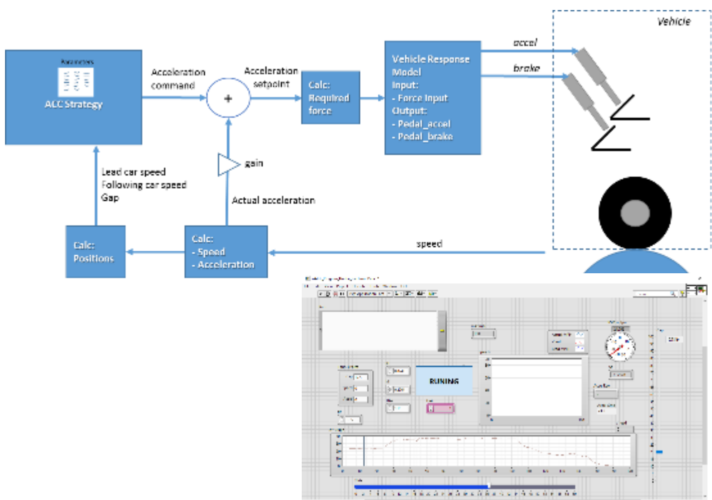
# Accomplishments: <u>Energy-Centric</u> CAV Laboratory – Robot Driver Adaptations: Eco-Launch and ACC

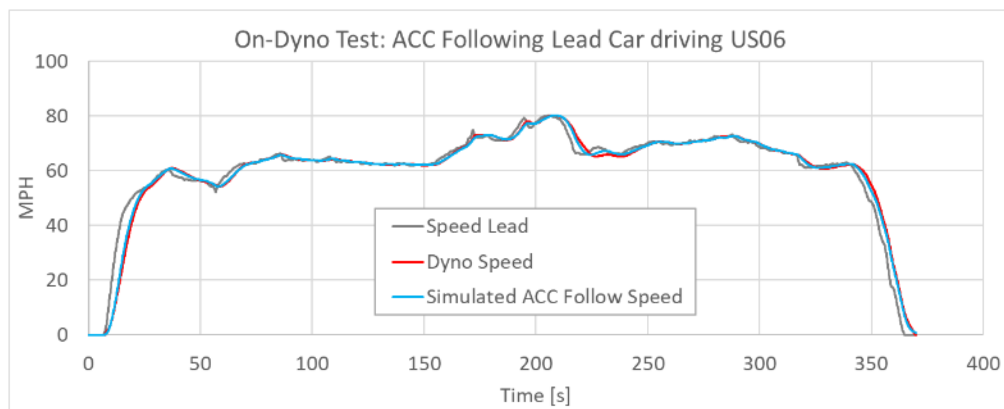



Repeatable Eco-Approach/Launch Trajectory



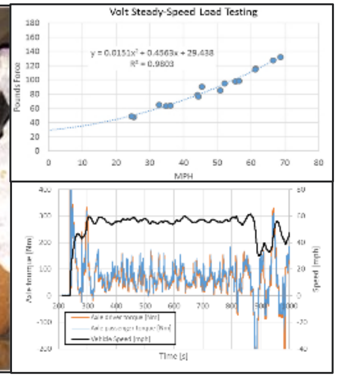

Vehicle's ACC was emulated with robotic controls (simulated lead vehicle and gap)



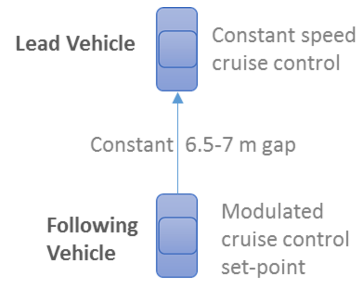



# Accomplishments: Tractive Load Measurement during Vehicle Platooning - Proof of Concept

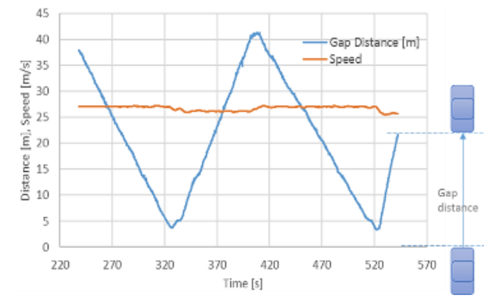
## Axle torque sensors can directly measure road-load differences during following



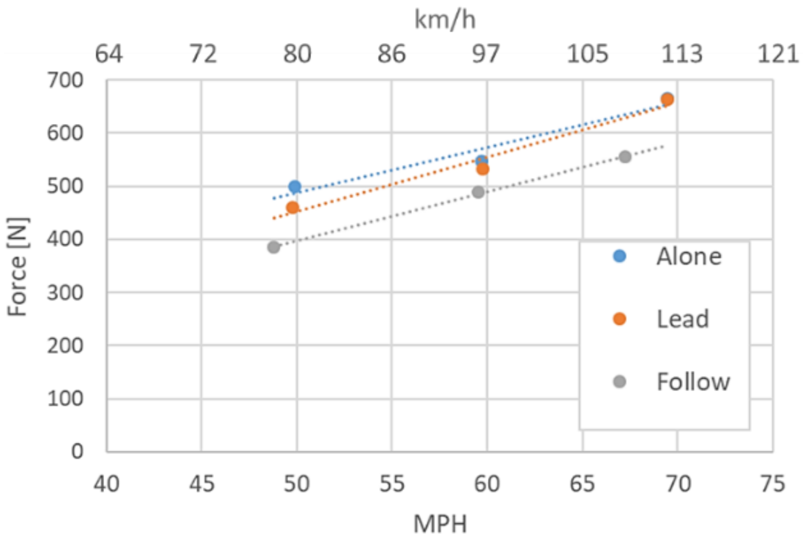

1) Fixed Distance



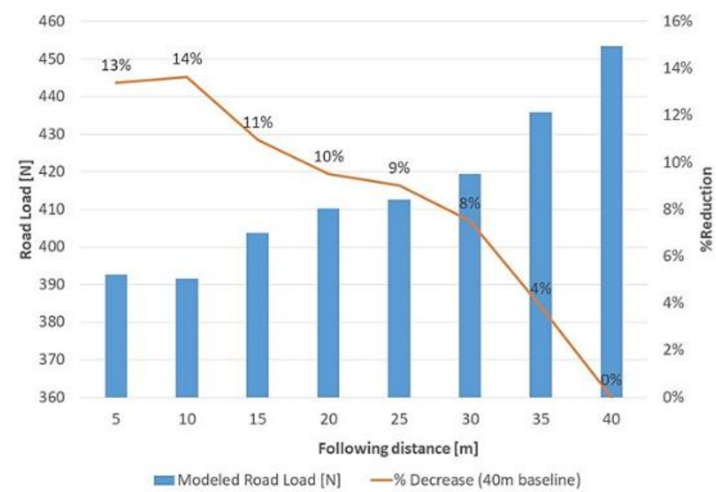

2) Dynamic Varying Distance




### Fixed Distance Results (6.5-7m)




### Preliminary Varying Distance Results



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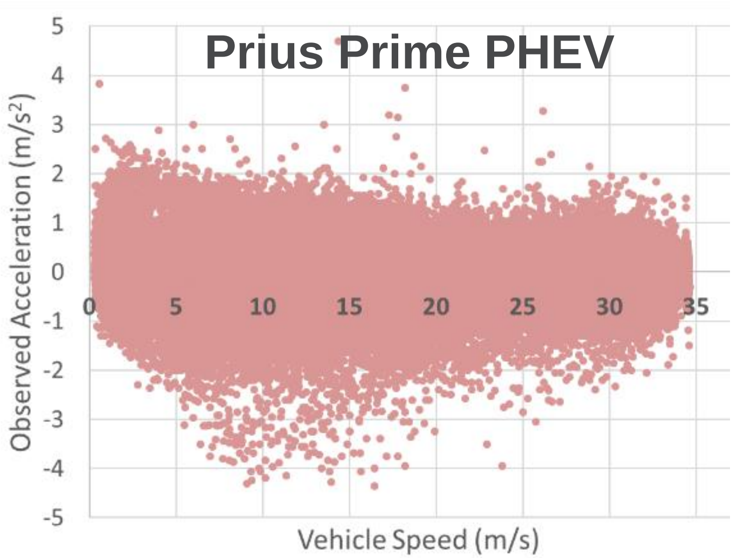
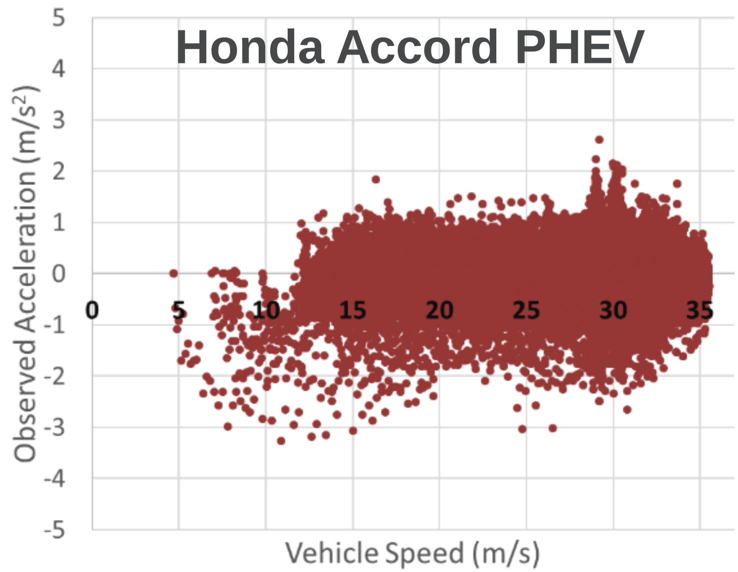
# Accomplishments: Simplified ACC System Characterization from On-Road Data Collection

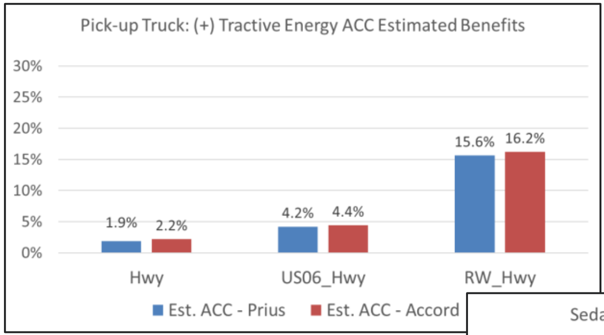


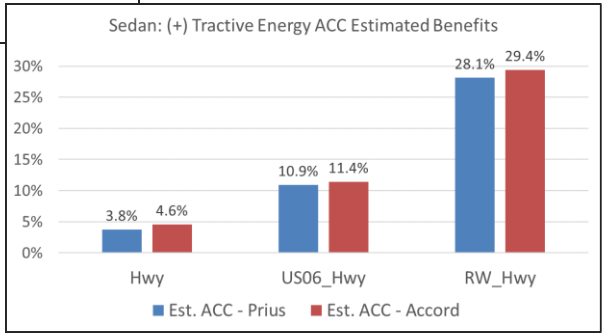




$$a_k = k_1(x_{k-1} - x_k - t_{hw} v_k) + k_2(v_{k-1} - v_k)$$ [1]

| | | |
|---|---|---|
| k1 | 0.0243 | dist |
| k2 | 0.2704 | speed |
| Ts | 1.18 | s |

| | | |
|---|---|---|
| k1 | 0.0180 | dist |
| k2 | 0.2405 | speed |
| Ts | 1.28 | s |

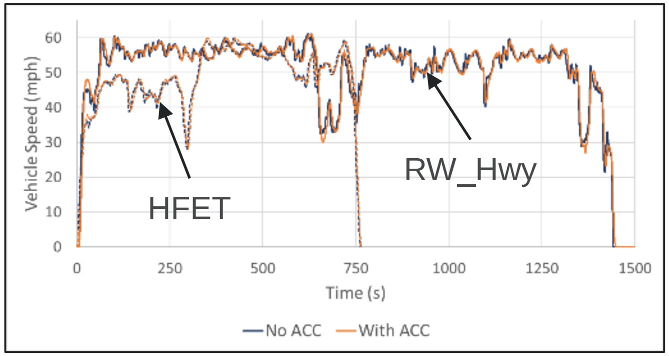




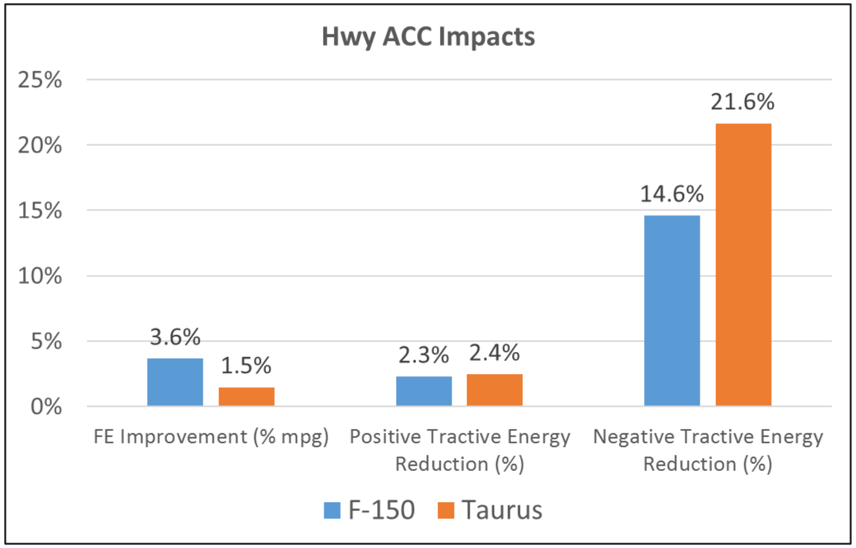
[1] Milanés, Vicente, and Steven E. Shladover. "Modeling cooperative and autonomous adaptive cruise control dynamic responses using experimental data." *Transportation Research Part C: Emerging Technologies* 48 (2014): 285-300.

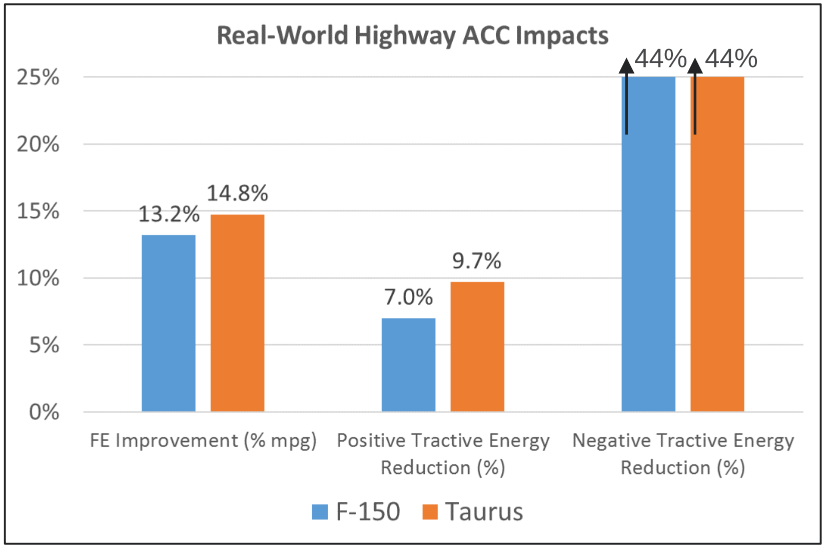
# Accomplishments: Highlighted Dynamometer Results - ACC Conventional Vehicle Impacts for "Highway" Driving




- Results vary significantly with cycle
- FE changes do not necessarily mirror tractive energy changes

- ACC cycles show fewer shifts (Taurus=62%, F-150=56% for RW-Hwy Cycle)
- ACC operation shows expanded top-gear utilization (26-29% for RW_Hwy)
- Aggregate engine usage similar, but fewer excursions with ACC



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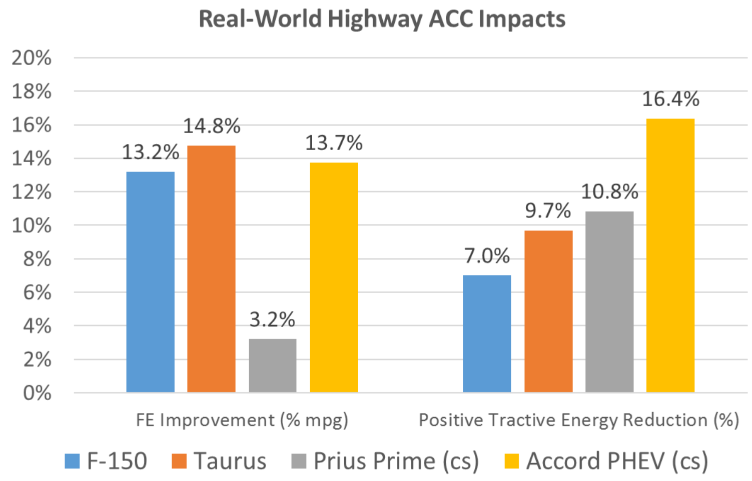
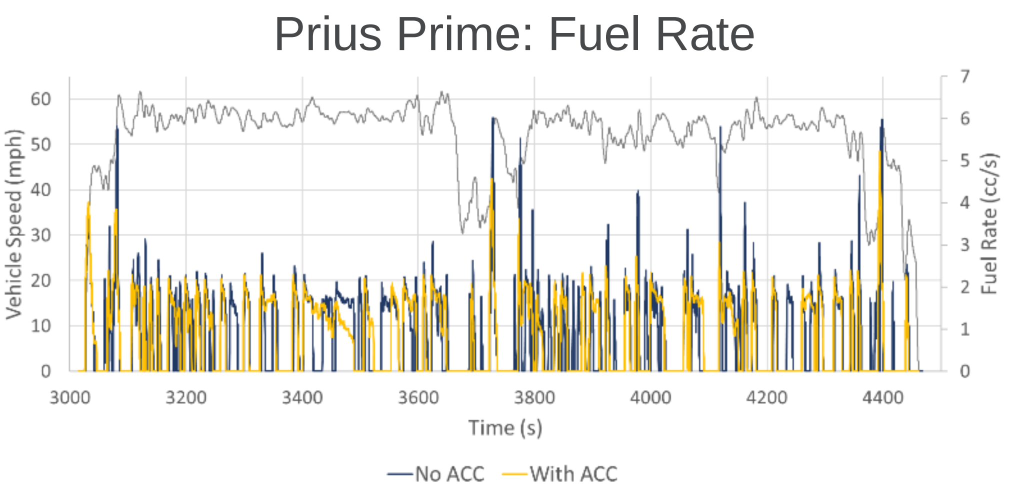
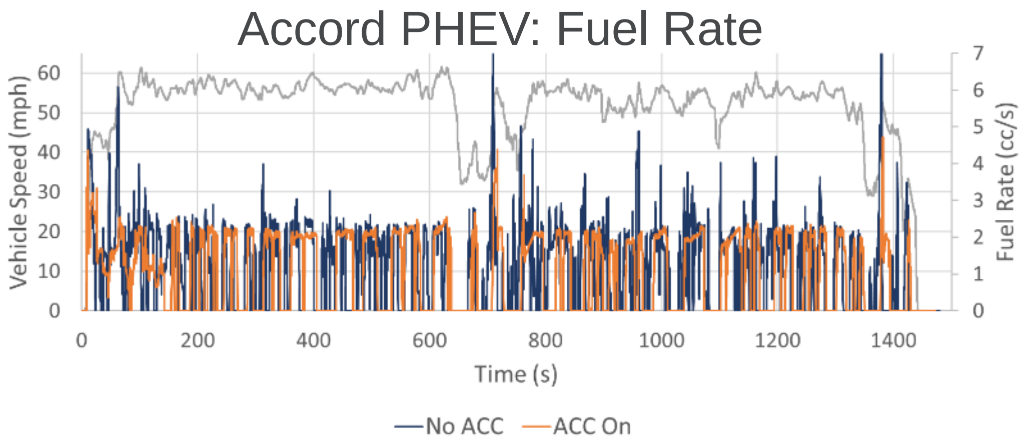
# Accomplishments: Highlighted Dynamometer Results - Hybrid vs. Conventional Vehicle Impacts




## Differences in ACC benefit for selected HEVs is a mix of control and architecture



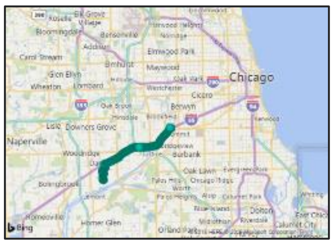

- Both HEVs show a significant decrease in regen. braking energy (38% Prius, 49% Accord)
- Accord shows a significant increase in EV operation
- Prius shows slight increase in EV operation

# Accomplishments: Preliminary On-Road ACC Analysis and High Fidelity Data Collection (collection on-going)

**Arterial**

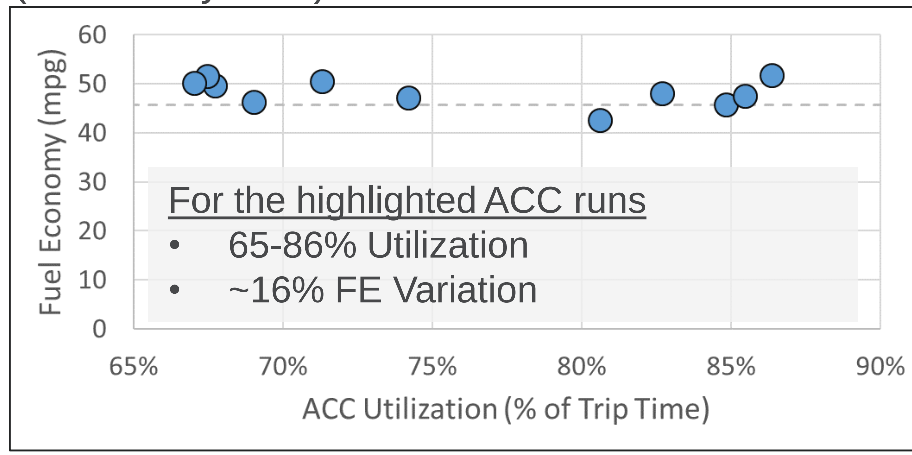

**Arterial Loop**

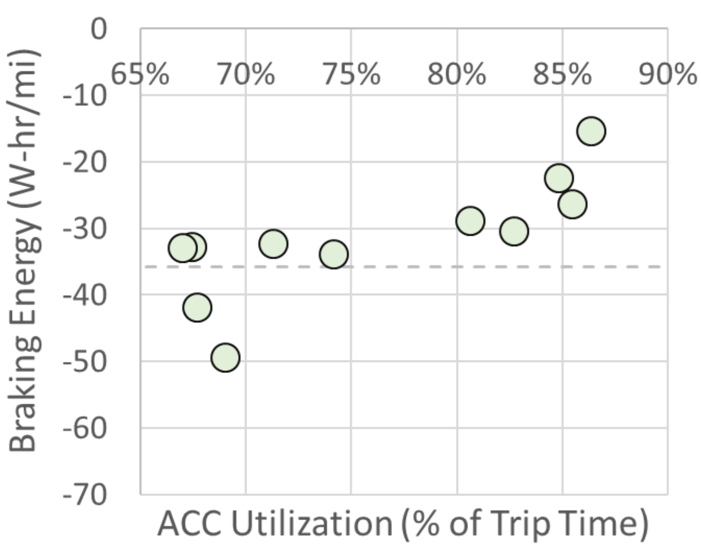

**Short Interstate**

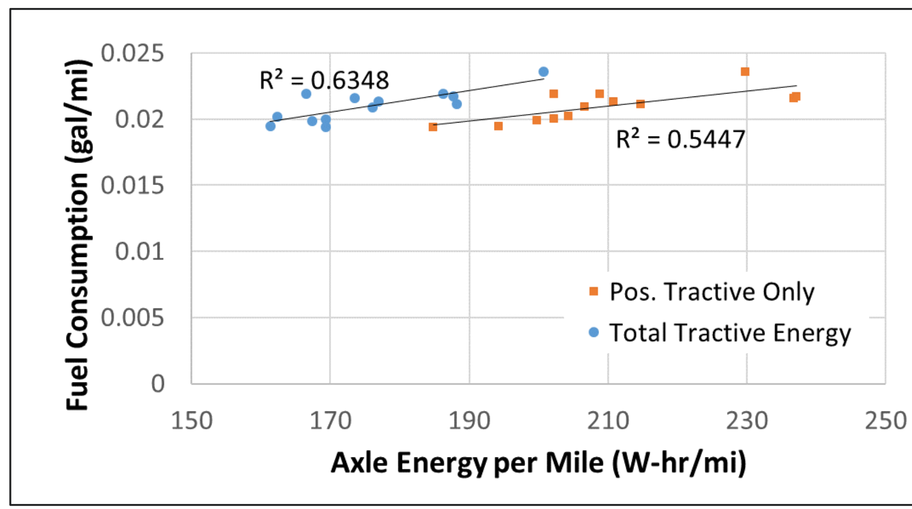



**Extended Interstate**


Highlighted EB Extended Interstate Trips
(mix of day/time)



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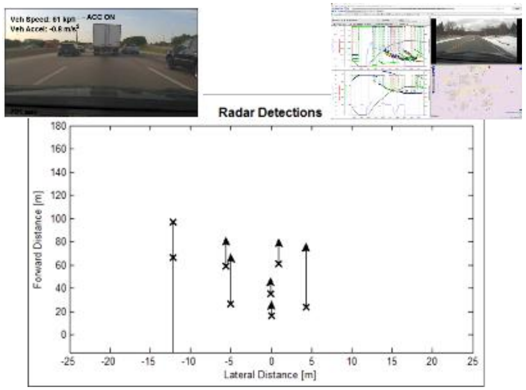
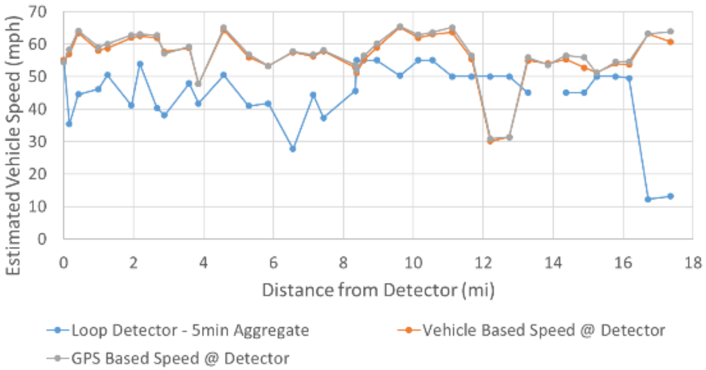
# Accomplishments: CAVs Enabled Awareness Opportunities

- Using just a radar system combined with GPS, many interesting opportunities arise

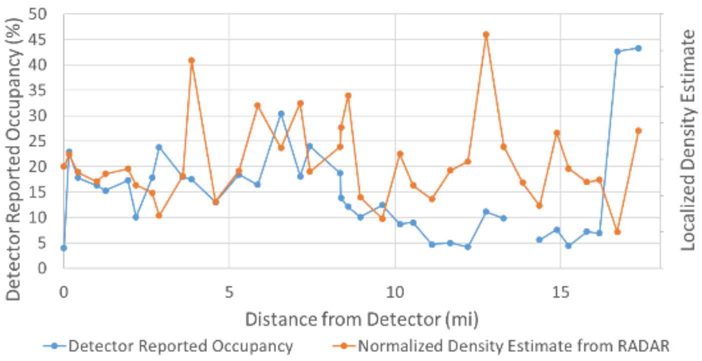



Extended Interstate

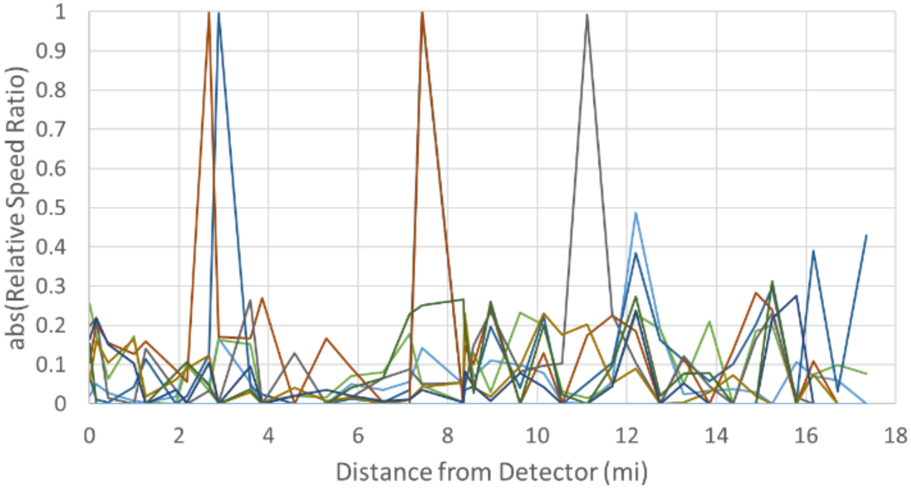

Supplemental Vehicle Speeds
(similar to GPS probe data)




Can Vehicle Radar Estimate Density?
(data collection/analysis on-going)




Motionless Objects Easy to Detect with Radar
(fuse with imaging to detect object – on-going)



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# Partners / Collaborators

## Argonne Vehicle and Mobility Modeling:

- Data & validation support for Autonomie, RoadRunner, SV-Trip, …

## DOE SMART - National Laboratory Partners:

- Primary Participants: ORNL, ANL, INL, LBNL, NRELC
- Coordination with CAVs and other DOE SMART Mobility pillars where/when applicable: AFI, CAVs, MDS, US

## University Partners:

- Illinois Institute of Technology

## DOE HPC-BigData for Mobility Design and Planning

- ANL, LBNL, ORNL, PNNL
  (not primary data set, but hopefully provide supporting data as needed)

# Highlighted Future Research

## Laboratory Testing

- Continued refinements/expansion of the emulation layers (perception and environment)
- Tighter integration within DOE M+S toolchain (Autonomie, RoadRunner, …)
- Evaluation of higher-level automation/coordination strategies

## On-Road Testing

- Expanded data collection scope (more vehicles, more locations, more technologies)

## Targeted On-Road & Track Testing

- Multi-vehicle/mixed-type platoon road-load estimation
- CACC and related strategy impacts for HEVs and BEVs

## CAVs Enabled Awareness and Sensing Opportunities

- Opportunities with L3-L4 sensors (i.e. LIDAR, multi camera/radar, etc.)
- Cyber-security implications of advanced sensing and connectivity within the larger EEMS operational environment

# Summary

## Relevance

- Disruption in transportation will transform how and what DOE instruments, tests, and evaluates to provide insights and support modeling efforts

## Approach

- 4 core hardware focused research thrusts (with interactions across)
- Focus on high-fidelity data across all testing environments

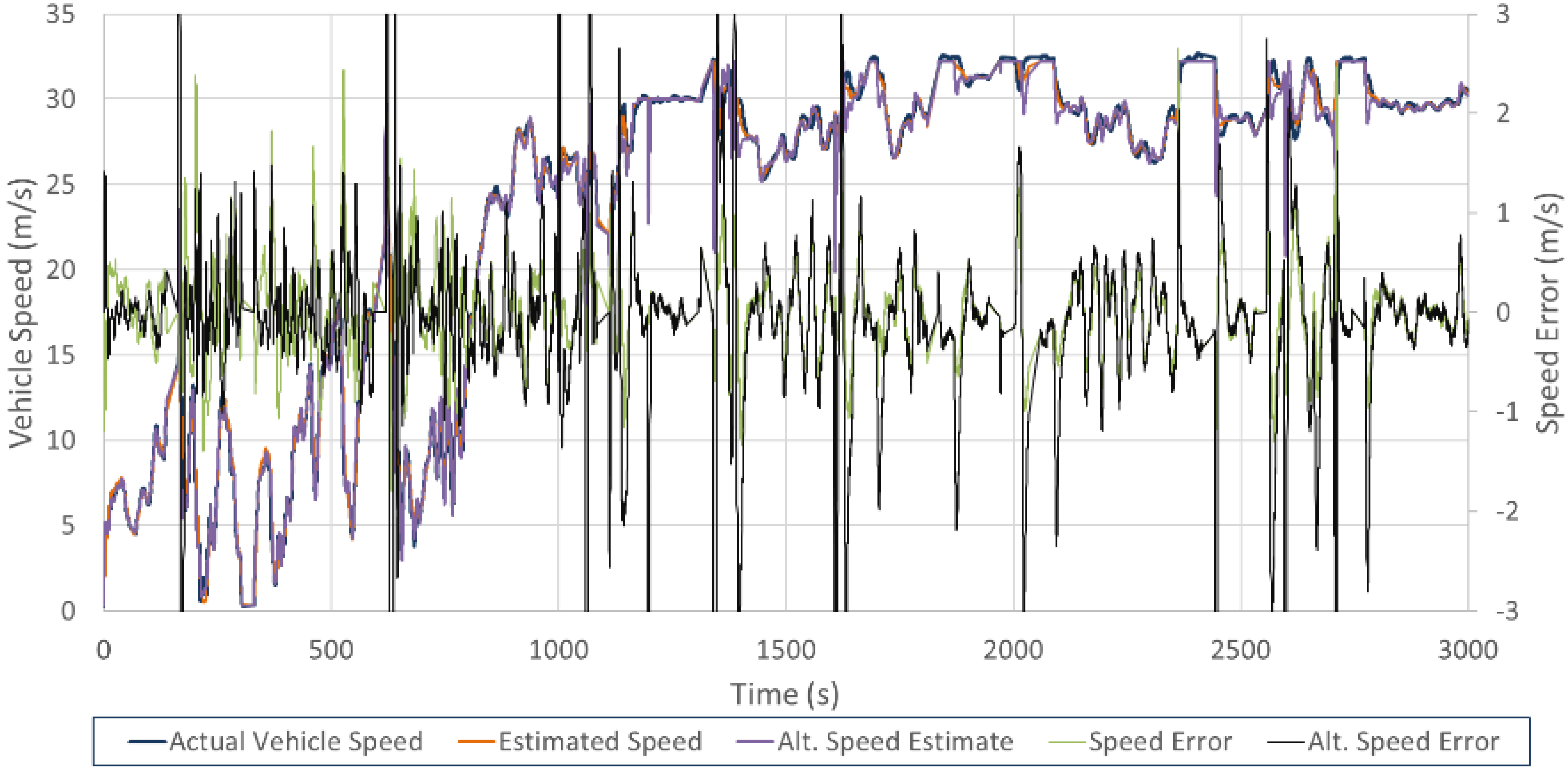
## Highlighted Accomplishments

- Foundational layer of an energy-centric CAVs laboratory
    - Robot driver provides a flexible and portable interface for evaluation of CAVs driving behaviors
- Modifying existing instrumentation practices may provide critical CAVs data for modeling and validation
- Dynamometer testing of even basic CAV features highlights a range of interesting trends and opportunities for further analysis
- Connectivity combined with location-awareness and emerging vehicle sensing opens a wide range of new possibilities

# Technical Back-up Slides

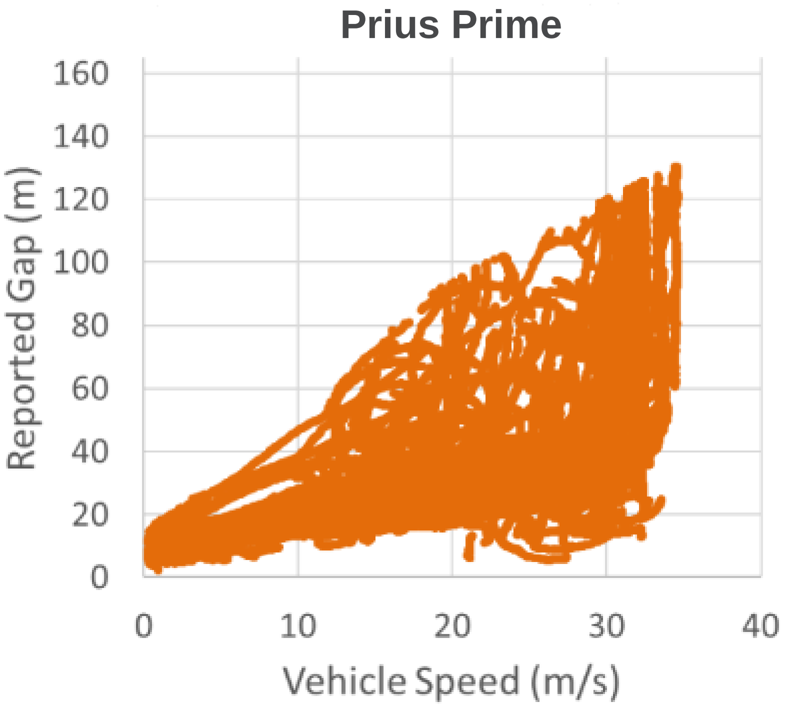
# Methodology Considerations: On-Road Data to Fit Simplified ACC Behavior

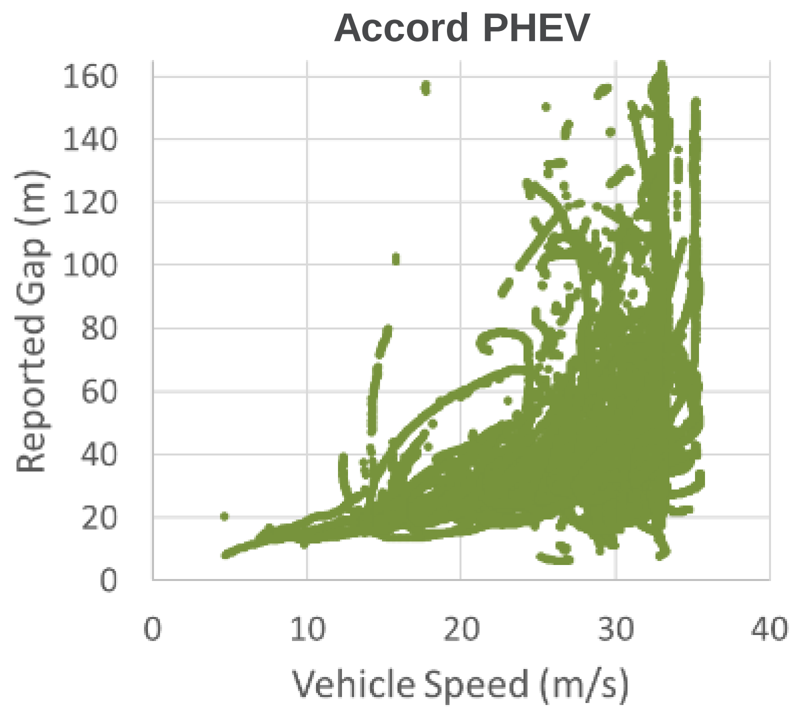
| | MSE | SumABS | Ref. | Ref. + Opt. | MSE-CACC |
|---|---|---|---|---|---|
| k1 | 0.02 | 0.02 | 0.23 | 0.23 | - |
| k2 | 0.28 | 0.27 | 0.07 | 0.07 | - |
| Ts | 1.25 | 1.18 | 1.1 | 1.78 | - |
| | | | | | |
| AVE SqErr | 0.450 | 0.459 | 2.460 | 2.155 | 0.450 |
| Sum ABS Err | 64246 | 63663 | 130724 | 119346 | 64241 |



# Methodology Considerations: Simplified ACC Fit Driven by Data Collected

$$a_k = k_1(x_{k-1} - x_k - t_{hw} v_k) + k_2(v_{k-1} - v_k)$$




**Prius Prime (gap <40m)**

| | Opt U-40 | Std All Data | OptU40 Time + Ref |
|---|---|---|---|
| k1 | 0.04 | 0.02 | 0.23 |
| k2 | 0.31 | 0.27 | 0.07 |
| Ts | 1.17 | 1.18 | 1.50 |
| | | | |
| Sum ABS Err (<40m gap) | 37649 | 39193 | 68013 |

**Accord PHEV (gap <40m)**

| | Opt U-40 | Std All Data | OptU40 Time + Ref |
|---|---|---|---|
| k1 | 0.04 | 0.02 | 0.23 |
| k2 | 0.30 | 0.24 | 0.07 |
| Ts | 1.19 | 1.28 | 1.19 |
| | | | |
| Sum ABS Err (<40m gap) | 18869 | 20883 | 30099 |

A more formalized methodology (or alternative testing methodology) would improve some of these common issues…